Fermilab

Precision in SBD* Measurement

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The precision of the Sample Bunch Display's measurement of bunch intensities is required for error determination of Accelerator Division's Luminosity calculations.

1 Beam Detection[1]

Tevatron and Main Ring beam currents are sensed by Resistive Wall Current Monitors located in the beam pipes; E49 for the Tevatron and E48 for the Main Ring. Voltage signals proportional to beam current, on the order of 2 mV/E9 for either Proton or Anti–Proton bunches, are routed to the RF control room at F0 by 3 inch hardline cables. These cables are terminate with Hewlett Packard Model 11850C 50Ω Power Splitters above the south racks in the RF control room.

2 Signal Processing

From the Tevatron hardline cable's power splitter one of the splitter's outputs is fed to a 50 ohm Input Pod (Model 54002A) for channel 1 of a model HP 54100 A/D Digital Oscilloscope. From the Main Ring hardline cable's splitter one of its splitter's outputs is fed to a 50 ohm Input Pod for channel 2 of the digital oscilloscope. Scope triggering is supplied from Tevatron Beam Sync and Tevatron $\bar{p}$ Beam Sync to scope input channels 3 and 4 respectively.

2.1 HP 54100 A/D Digitizing Oscilloscope

During bunch measurement the scope's sweep speed (`T:TPHSWP`: proton horizontal sweep speed; `T:TAHSWP`: anti–proton horizontal sweep speed) is set at 2ns/division. The oscilloscope's vertical scale is automatically selected based on amplitude of the input signal. Standard selected scales are: 100mV/division; 40mV/division; 20mV/division etc... depending on bunch intensity.

2.1.1 Specifications and Operating Characteristics[2]

1. Bandwidth (-3db): dc to 1 GHz

*Sample Bunch Display

2. Transition Time (10% to 90%): $\leq 350ps$

3. Deflection Factor (full–scale = 8 divisions): 10mV/div to 1V/div in 1–2–5 steps.

4. DC Accuracy, Single Voltage Marker: ±3% of full–scale; ±2% of offset[1].

5. Digitizer resolution: 7 bits (1 part in 128).

6. Digitizing rate: up to 40 megasamples/second.

7. Data Display Resolution: 501 points horizontally by 256 points vertically.

8. Display Mode (**Averaging**): The number of averages can be varied from 1 to 2048 in powers of 2. On each acquisition, $1/n$ times the new data is added to $(n-1)/n$ of the previous value at each time coordinate. Averaging operates continuously; the average does not converge to a final value after n acquisitions.

2.1.2 Discussion of Averaging Mode

As the input signal is digitized, each data point is assigned a time coordinate relative to the trigger. In the averaging mode the oscilloscope calculates the average of the most recent data point with the previous values in the same time slot. One can define the number of data points that are to be averaged from 2 to 2048 (2^{11}) in powers of 2. Each average is calculated from data acquired for each time slot—data for adjacent time slots is not averaged together.

If 8 is chosen for the number of averages, $1/8^{\underline{th}}$ of the vertical value of each new data point will be added to $7/8^{\underline{th}}$ of the value previously in that time slot. If 16 averages had been selected, $1/16^{\underline{th}}$ of the new data would be added with $15/16^{\underline{th}}$ of the previous value.

The effect of using averaged mode is to cancel out all phenomena that are not time related to the trigger event, i.e., noise and nonrecurring events.[2]

2.1.3 Output

Connection with the HP is made via a HP–IB Interconnection cable. The Data bus consists of 8 data lines ($2^8 = 256$) . Data is in the form of 16032 bytes preceded with four header bytes. Each bit in the binary block represents one pixel on the oscilloscope screen. Since there are 256 pixels in each column of

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[1] When driven from a 50Ω source.

[2] §7-12. AVERAGED, *HP Operating and Programming Manual Model 54100A/D Digitizing Oscilloscope*, January 1985

the data displayed, it takes 32 bytes (265/8) to represent one column of the display. Thus $32 bytes/column * 501 columns = 16032 bytes$ for the entire data array.

2.2 The Sample Bunch Display[3]

2.2.1 Intel Crate

Located in the lower portion of Rack S MON–2 in the RF control room at F0 directly beneath the HP Digital Oscilloscope. This crate and the HP 54100 A/ D Digital Oscilloscope make up the majority of the Sample Bunch Display hardware. The HP–IB Interconnection cable connects directly to one of the crate boards. Additionally the crate has rear connections to: Proton Mountain Range Trigger Generator; Anti–Proton Mountain Range Trigger Generator; Fast Measurement SBD Trigger Gate; Tevatron Beam Sync; Tevatron $\bar{p}$ Beam Sync; TCLK (Tevatron Clock); Host connection to to the CAMAC 080 Smart Module; and Video Output signal. Located within this crate is the board containing the brain of the SBD–the Motorola 68000 μp.

2.2.2 Motorola 68000 Microprocessor Chip

This 16–bit processor controls the sample bunch display. It operating program is downloaded via console applications program page D43. The correct file to open is: `RSX$FSHARE_APPLICAT_TEVATRON_MISC:DNLDCSC.TX3` for front end: `TRF`, module: `MISC`, and house: `SB`. After a successful download the Sample Bunch Display will default to setup mode (`T:SBMODE = 0`).

2.2.3 CAMAC 080 Smart Module[4]

This module provides the interface between the CAMAC environment (8–bits) and the 68000 Microprocessor (16–bits). The card is located in slot 21 of crate $85, DEC–R. The crate is located in the Rack S MON–3 in the RF control room at F0.

2.2.4 Modes of Operation

The SBD mode control parameter is `T:SBMODE`.

`T:SBMODE = 0` This is TEVATRON SETUP MODE. It is used for aligning bunch intensity signals on the oscilloscope screen. Only in this mode can changes to setup parameters be made. Changes to setup parameters in modes other than Setup will be reflected but ignored and restored from current operating conditions.

`T:SBMODE = 1` This is MAIN RING SETUP MODE. Similar to `T:SBMODE = 0` but for Main Ring setup parameters.

`T:SBMODE = 2` This is MEASUREMENT MODE.

`T:SBMODE = 3` This is FAST MEASUREMENT MODE. The Tevatron Sequencer (T48) will selected this mode at the start of shot setup.

`T:SBMODE = 4` This is DISPLAY MODE. In this mode six waveforms will be alternately accumulated and displayed between protons and anti–protons, using the SETUP MODE parameters for horizontal position and vertical sensitivity.

`T:SBMODE = 5` This is LOCAL MODE. In this mode the digital oscilloscope is allowed to be returned to local mode for local use. Changes made in this mode may affect the operation of other modes.

`T:SBMODE = 6` This is SLOW MEASUREMENT MODE. In this mode pulse widths, sigmas, and intensity measurements are made of each bunch intensity signal. Horizontal sweep speed is automatically set to 2nsec/div and vertical setup parameters do not reflect current vertical sensitivity– since the oscilloscope is autoscaling the vertical sensitivity based on input signal amplitude.

The analysis program checks that data was obtained while the SBD was in the SLOW MEASUREMENT MODE.

3 Data Analysis

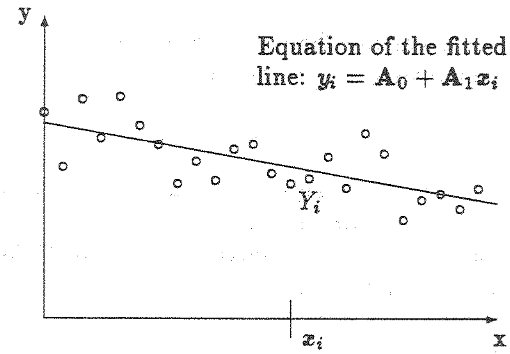
3.1 Analysis Program

The program used Dataview [5] to retrieve the stored data of interest: sample bunch intensities (`T:SP1INT` thru `T:SP6INT`); the mode of operation of the SBD (`T:SBMODE`); and the number of averages that the SBD's μp is having the HP oscilloscope perform (`T:SBDAVE`). The data was Datalogged at 120 second intervals with the exception of `T:SP1INT` which was Datalogged at 60 second interval. For the Tevatron Colliding Beam Store under analysis a time interval (*3 hours*) was selected which was small compared to beam intensity halflife. Hence it was assumed that the data could be linearly ($1^{\underline{th}}$ order polynomial) fitted over the chosen time interval.

Eight Tevatron stores, taking place between 19-Feb-1989 and 27-Feb-1989, were chosen for analysis. The chosen stores yielded 47 three hour interval (*time intervals were chosen such that scraping had been completed and that a whole number of 3 hour intervals of stored beam existed*); multiplying by the six proton and six anti–proton bunches resulted in 282 intervals of analysis.

3.1.1 Example Data

The following figure illustrates a $1^{\underline{th}}$ order polynomial fit to sample data. The value of the fitted line at the start of the interval is $\mathbf{A}_0$. The SLOPE of the fitted line is $\mathbf{A}_1$. And y_i is the unknown value of the fit for a given Y_i at the chosen x_i of interest.



Data set containing N number of data points

3.1.2 Linear Least Square Fit

Continuing with the notation of the previous figure: a LEAST SQUARE FIT determines the unknown in terms of known quantities to be:

$$y_i = \left(\frac{\sum Y_i \sum x_i^2 - \sum Y_i x_i \sum x_i}{N \sum x_i^2 - \sum x_i \sum x_i} \right) + \left(\frac{N \sum Y_i x_i - \sum Y_i \sum x_i}{N \sum x_i^2 - \sum x_i \sum x_i} \right) x_i$$

Where all summations in the above equation are:

$$\sum_{i=1}^{N}$$

In the above figure the calculated y_is are connected to show that the equation for y_i does produce a linear fit. The analysis program calculated the y_is for each of the given Y_is.

3.1.3 Sum of the Residuals

Based on the determined LEAST SQUARE FIT the analysis program calculated the variable ERROR, E, which is the Sum of the Residuals squared. ERROR is:

$$E = \sum_{i=1}^{N} (Y_i - y_i)^2$$

Where a Residual is the difference between a given data point and the fitted line.

3.1.4 Sigma

With the Sum of the Residuals squared calculated the analysis program goes on to calculate SIGMA; where the variable SIGMA is:

$$\text{SIGMA} = \sqrt{E/N}$$

The determined SIGMAs are the precision of the Sample Bunch Display's measurement of bunch intensity over the chosen time interval.

3.1.5 Units

The Sample Bunch Display returns the value of bunch intensity in units of # of Protons (or Anti–Protons) times ten to the $9^{\underline{th}}$, (E9). And the units of ERROR are # of protons (E9) squared. The units of SIGMA are the same as bunch intensity, # of protons (E9).

3.2 Bad Data

The analysis program checks datalogged data for repeating data; the rate at which the datalogger reads and stores data to disk is asynchronous with the sampling rate (*also called "measurement cycle time"*) of the sample bunch display. The sampling rate of the sample bunch display is determined by its mode (`T:SBMODE`), the number of averages being performed (`T:SBDAVE`), and whether or not the sampled bunch is being displayed (for each of `T:SDMASK`'s bit, the parameter when viewed in RAW DATA is a 16–bit word [e.g. `OFFF`], that matches the associated bit of `T:SBMASK` one of the bunch profiles will be displayed on MR South channel 22 of the video system). If identical consecutive bunch intensities were datalogged (indicating that the 'read and store data call' was performed by the Datalogger before the SBD reread and updated the bunch intensity) the repeated data points were not used in analysis; this would have been unevenly weighting those data points.

It has been found that the Datalogger will occasionally store data on disk that is very inconsistent (*orders of magnitude different*) with actual bunch intensity. Often the reason for the bad data is known. As an example during store # 2006 the CAMAC 080 smart module initialized itself and the SBD μp had to be rebooted. Between death and reboot no SBD data was available yet store beam was present in the Tevatron. During that interval 13 bad data points were logged in each of the proton and anti–proton Dataview data files; corrective action was to manually edit the data file prior to running the analysis program. The time interval in question did produce SIGMAs in the expected range; SIGMA is the square root of ERROR divided by the number of data points.

Other inconsistent data points infrequently arose for reasons not well understood. These were treated as bad data and not used in analysis. Possible reason is an error in the Datalogger storing data on disk; these points were found after analysis during review of the output data. In these cases output data showed very large ERRORs and SIGMAs for the selected time interval that was inconsistent with adjacent intervals. A review of the input data files confirmed the fact that a bad data point existed. Editing out the bad point and rerunning the analysis program yielded results consistent with adjacent intervals.

3.3 Results

The plot and two histograms on the next three pages show the final results of this experiment. The figures were made with the Topdrawer[6] plotting package.

Figure 1 is a plot of calculated SIGMAs for all time intervals under analysis verses the MEAN value of sample bunch intensity. The large SIGMAs for some MEAN bunch intensities of about 60E9 is due to the autoscaling feature of the HP Oscilloscope. During these time intervals the oscilloscope had started measuring proton bunch intensity's on the 100mV/division vertical scale; then as the bunch intensity decreases due to beam halflife the oscilloscope automatically, based on the microassembler code of the SBD μp, rescales to the 40mV/division vertical scale. The two areas of tightly grouped data correspond to the nominal vertical scale ranges: protons (*in the 60E9–40E9 range*) of 40mV/division; anti–protons (*in the 30E9–15E9 range*) of 20mV/division.

Figure 2 shows a histogram of each of the SIGMA's from figure 1. The two areas of tightly grouped data are now displayed as two strong peaks. It appears that a third peak centered about **0.25E9** is visible; this would correspond to the 100mV/division oscilloscope vertical scale. To obtain a sharper third peak more data would need to be analyzed. Additionally, carefully picking the time intervals of analysis so as not to include times when the oscilloscope rescales to the 40mV/division scale would improve the sharpness of the third peak. It is the discontinuity in measuring data that results in large SIGMAs.

The third and final figure is an increased resolution of the data histogrammed in figure 2. The bin width was reduced from 0.003 to 0.002 and histogramming range was limited to 0.2. The two strong peaks remain visible.

The results of this experiment are the values of the two peaks in figure 3:

- A SIGMA of **0.075E9** for the oscilloscope's 20mV/division vertical scale.
- A SIGMA of **0.12E9** for the oscilloscope's 40mV/division vertical scale.

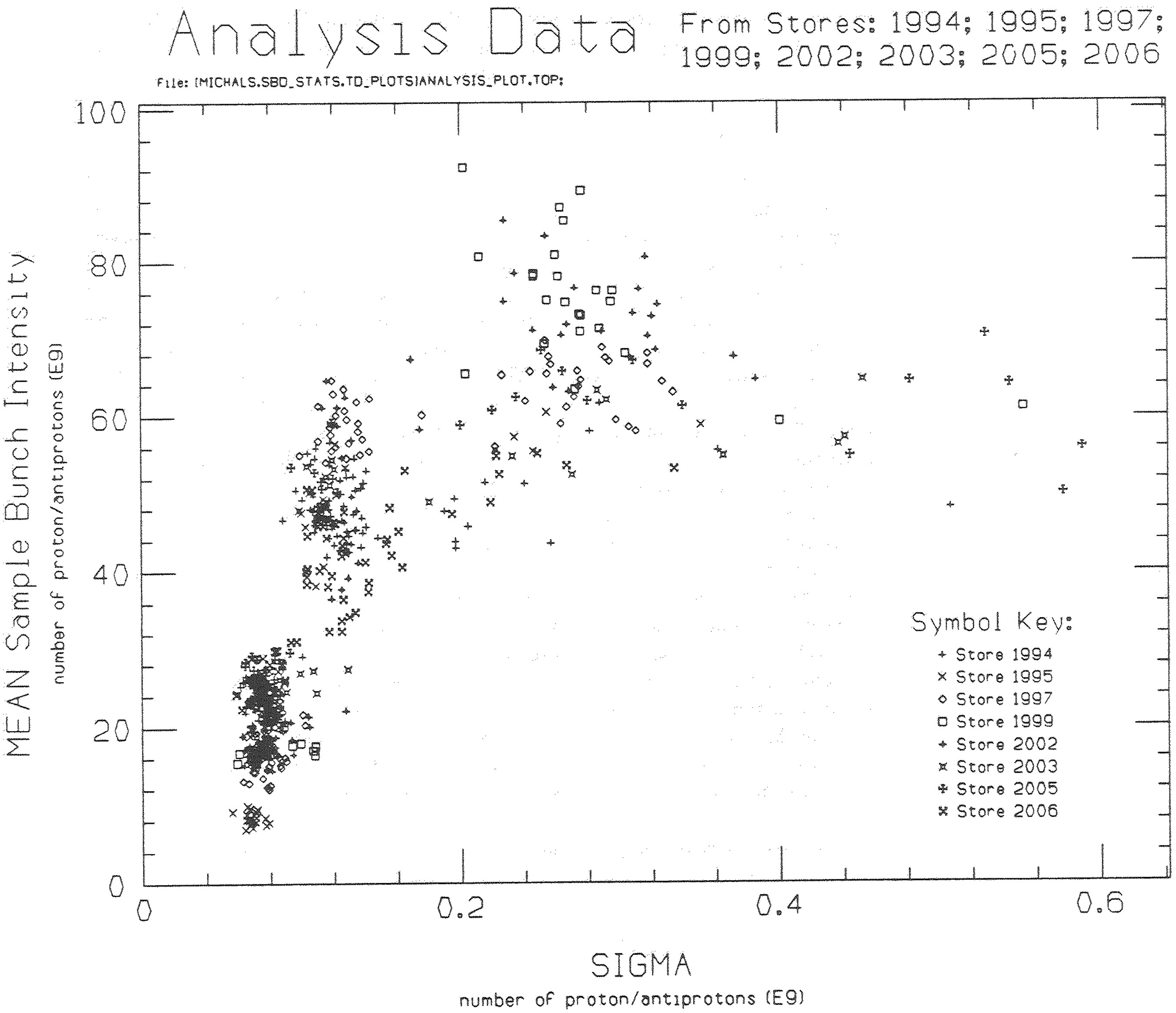
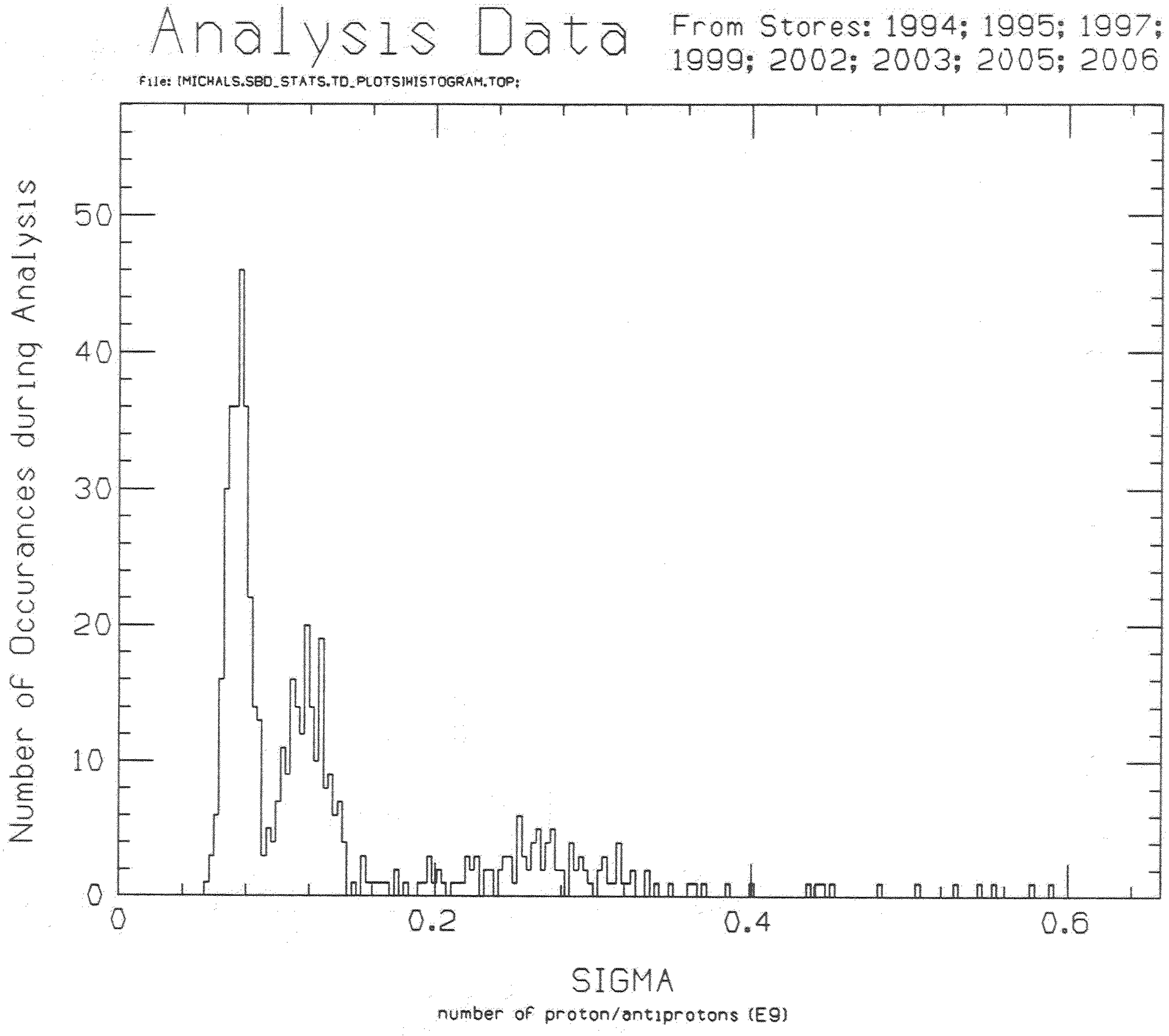
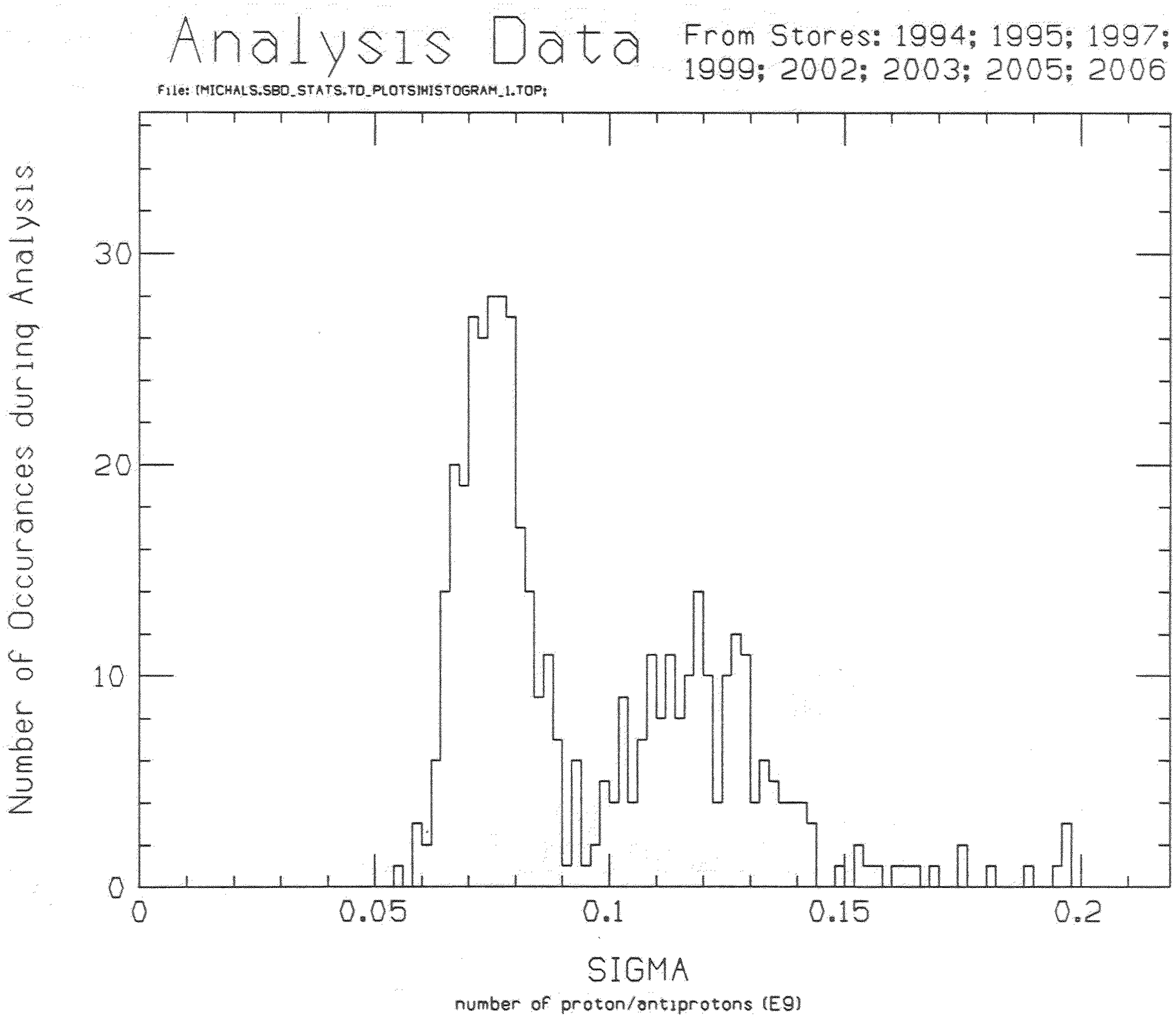

Analysis Data
From Stores: 1994; 1995; 1997; 1999; 2002; 2003; 2005; 2006
File: [MICHALS.SBD_STATS.TD_PLOTS]ANALYSIS_PLOT.TOP;
MEAN Sample Bunch Intensity
number of proton/antiprotons (E9)
SIGMA
number of proton/antiprotons (E9)
Symbol Key:
Store 1994
Store 1995
Store 1997
Store 1999
Store 2002
Store 2003
Store 2005
Store 2006
0
20
40
60
80
100
0
0.2
0.4
0.6

Figure 1



Analysis Data
From Stores: 1994; 1995; 1997; 1999; 2002; 2003; 2005; 2006
File: [MICHALS.SBD_STATS.TD_PLOTS]HISTOGRAM.TOP;
Number of Occurances during Analysis
0
10
20
30
40
50
0
0.2
0.4
0.6
SIGMA
number of proton/antiprotons (E9)

Figure 2



Analysis Data
From Stores: 1994; 1995; 1997; 1999; 2002; 2003; 2005; 2006
File: [MICHALS.SBD_STATS.TD_PLOTS]HISTOGRAM_1.TOP;
Number of Occurances during Analysis
0
10
20
30
0
0.05
0.1
0.15
0.2
SIGMA
number of proton/antiprotons (E9)

Figure 3

3.4 Statistics[7][8]

Defining some common statistical terms allows me the opportunity to typeset a few more formulae with LaTeX[9].

3.4.1 Mean

For N measured values of x the MEAN value of x is:

$$X_N \equiv \overline{x} = \sum x/N = \frac{1}{N}\sum_{i=1}^{N} x_i$$

The MEAN of an infinite number of measured values of x would be the true value of x. But in the case of Sample Bunch Intensity there is a decay in bunch intensity over time and since each measurement takes a finite amount of time thus merely measuring forever would not result in the true value of x. The bunch intensity would have decayed to zero before the infinite number of measurements could be achieved.

3.4.2 Deviation

The DEVIATION of the $i^{\underline{th}}$ measurement from the MEAN is:

$$\delta_i = x_i - \overline{x} = x_i - \frac{1}{N}\sum_{i=1}^{N} x_i$$

3.4.3 RMS Deviation

The ROOT MEAN SQUARED (RMS) DEVIATION of x:

$$\sigma_N(x) \equiv \sigma_N = \left(\sum_{i=1}^{N} \frac{\delta^2}{N}\right)^{\frac{1}{2}} = \left[\sum_{i=1}^{N}\{\left(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i\right)^2 /N\}\right]^{\frac{1}{2}}$$

4 Concluding Remarks

This experiment, unfortunately, does not address the question that was proposed by Dr. David Finley: Does the number of averages that the SBD μp has the HP Oscilloscope perform effect the resulting measured value of bunch intensity[10]?

The ability of the SBD to return increased accuracy data is currently limited to 10–bits of resolution. This limitation is imposed by the SBD's software limiting the number of observable averages to: 1, 2, 4, or 8[11].

I wish to thank Dr. David Finley for his assistance during this project. Also I wish to thank Bob Mau for allowing me the time to work on this project. And finally I wish to thank John Payne for his help in understanding how the SBD operates.

References

[1] Drawing number $1680.00 - ED - 159227$: Energy Doubler/Saver Sample Bunch Display Interconnection Diagram.

[2] HP Operating and Programming Manual Model 54100 A/D Digitizing Oscilloscope. printed: January 1985.

[3] John Payne. Revised Operation Bulletin #1080: Sample Scope Operating Guide (Tevatron P/P-Bar Bunch Display/Analysis System)

[4] David Johnson. *The Fermilab Accelerator Control System, Volume* II. June 1986

[5] See Vax on line help (`$HELP DATAVIEW`).

[6] Roger B. Chaffee. *Top Drawer. Computation Research Group, Stanford Linear Accelerator Center.* Revised November 1980.

[7] N. C. Barford. *Experimental Measurements: Precision, Error and Truth.* Addison-Wesley Publishing Company, Inc. 1967.

[8] Philip R. Bevington. *Data Reduction and Error Analysis for the Physical Sciences.* McGraw-Hill Book Company. 1969.

[9] Leslie Lamport. LaTeX: A Document Preparation System. Addison-Wesley Publishing Company, Inc. 1986.

[10] Dr. David Finley. Letter to Bob Mau dated September 20, 1988. Subject: Proposal for SBD Averaging Determination. (Also see log enter in ED14 page 197).

[11] John Payne. log entry page 299 of ED14.